Modeling the mechanical behavior of composite metal plastic pipes subject to internal pressure and external soil and traffic loads

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Abstract: In the present paper, numerical nonlinear models for the mechanical behavior of metal-reinforced plastic pipes (MRP) in destructive tests are developed to analyze the stress-strain state (SSS) in such pipes during loading. The paper focuses on the nonlinear response of composite pipes consisting of two plastic layers and a steel tube layer. A parametric analysis regarding the internal pressure and external loading has been conducted, using the DOE method. Moreover, the effect of pipe radius on the mechanical response has been studied through three different case studies. For the computation of the stresses and displacements the general finite element software ANSYS is used.

Key-Words: - Composite Pipes, Finite Element Method, Nonlinear Numerical Models, Steel Reinforcement

1 Introduction

In the industry today many types of pipes are used: steel reinforced concrete, solid wall plastic, glass reinforced plastic, spirally wound plastic, corrugated plastic, steel reinforced plastic e.t.c. It is also known that composite pipes have many potential advantages over conventional pipes, such as high specific stiffness and strength, good corrosion resistance and thermal insulation. The first composite alternatives to steel pipelines consisted of composite pipes based on thermoset matrices. However, increasing demands, involving high temperature resistance and the need for damage tolerance and flexibility often exceed the capabilities of thermosets. Contrary thermoplastics, polyethylene (PE or HDPE), satisfies these constraints.

For the stress analysis of cylindrical multi-layered composite structures, many methods for stress and displacement analysis have been proposed during the past years. The static behaviour of thin shell panels has been investigated using two-dimensional shell theory based on the Love–Kirchhoff hypotheses. Chandrashekhara and Kumar presented and assessed this shell theory. The laminated shell theory provides an accurate solution for thin-walled cylinders but for thick-walled cylinders 3D elasticity solutions are required for the determination of the stresses. Further Chandrashekhara and Nanjunda Rao furnished an exact three-dimensional elasticity solution for an infinity transversely isotropic cylindrical shell under arbitrary discontinuous load using a displacement function approach. However this solution is based on a system of partial differential equations with variable coefficients. Therefore the extension of this solution for an anisotropic cylindrical shell panel with arbitrarily stacking sequence is quite complex if not impossible. In order to overcome these difficulties, an approximation suggested by Soong was used in order to reduce the variable coefficients to constant ones, by assuming that the ratio of thickness of each ply to its middle surface radius is small and can be neglected. Based on the last approach, Guedes presented an approximate 2-D elasticity solution for stresses and deflections analysis of laminated cylindrical pipes under transverse loading conditions, which showed very good accuracy compared with a 2D-FEM simulation done e.g. using ABAQUSTM 2-D elements CPE8R (plane strain continuum) with 21,600 elements, distributed in skin (4 layers) and core (40 layers).

In the present work, the mechanical behaviour of metal reinforced composite pipes subject to internal pressure and external loading is considered. Numerical nonlinear models are developed to analyze the stress-strain state (SSS) in such pipes during loading. The paper focuses on the nonlinear response of composite pipes consisting of two HDPE layers and a steel tube layer. A parametric analysis regarding the internal pressure and external loading has been conducted, using the DOE method.

In addition, we rely for these analyses totally on existing CAE software: the steel tube cylinder and the polyethylene cover are modelled as different solid parts that are assembled using Autodesk Inventor®.

The solid model is –then- introduced for processing with ANSYS®.

The current paper is organized as follows: In the second chapter the composite metal plastic pipe subject to internal pressure is considered. In the third chapter the composite pipe is subject to external soil and traffic loads. In chapter 4 the mechanical behaviour of the composite pipe under combined loads is investigated and finally in chapter 5 conclusions are drawn.

2 Composite metal plastic pipe (CMP) subject to internal pressure

The metal reinforced pipe has an internal diameter d_m=150 mm, a length L=50 mm and its thickness is t=5 mm. The thickness of the steel tube layer is t_s=1 mm and of the HDPE layer is t_{HDPE}=2 mm. The CMP pipe is subjected to internal pressure p=3.5 MPa. Only half of the pipe is modelled using Autodesk Inventor® because of the symmetry of the problem.

Fig. 1: Solid model of MRP pipe

The model is meshed using ANSYS® with the parameter Relevance (R) of the meshing generator equal to R=100. The mesh is shown in Figure 2, and has 9433 nodes and 2860 elements: 1232 are 20-node quadratic hexahedron body elements and 1628 are contact elements. The boundary conditions are shown in Figure 3. Bilinear isotropic hardening is considered for both materials. Their properties are shown in Table 1.

	Steel	HDPE
Yield Strength	250	25
Tangent Modulus	10000	50

Table 1: Material Properties

The computed displacements are presented in Figure 4. The undeformed position of the pipe is shown in the same figure as a wireframe. The equivalent stresses of the HDPE and steel tube layer are shown in Figures 5 and 6 respectively. The developed stresses are almost uniform without any significant deviations. Further, the mechanical behaviour of the CMP pipe has been studied for a range of internal pressures ranging from p=3 to 8.5 MPa. The computed stresses of the HDPE layer are shown in Figure 7, of the steel tube layer in Figure 8 and the displacements in Figure 9. As it can be seen from the figures the nonlinear behaviour of the CMP pipe is found for p=4 MPa, where steel goes into the plastic region. The HDPE layer remains in the elastic region.

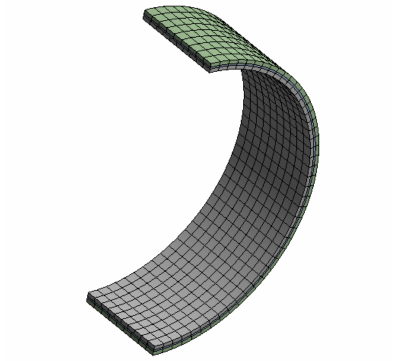

Fig. 2: Finite Element mesh of MRP pipe

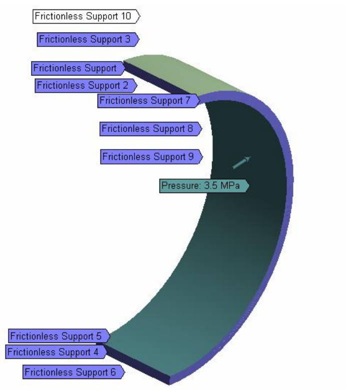

Fig. 3: Boundary conditions

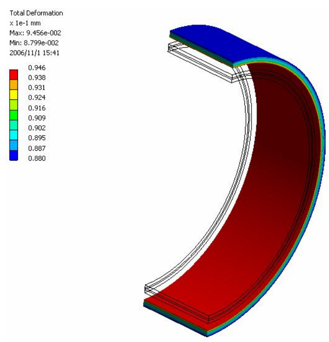

Fig. 4: Total displacements

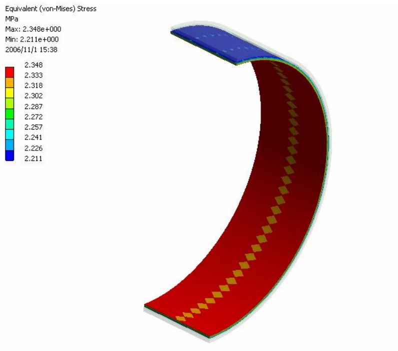

Fig. 5: Equivalent stresses of HDPE layer

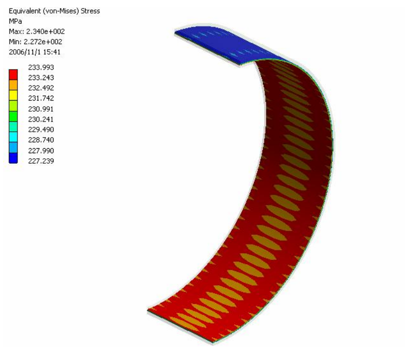

Fig. 6: Equivalent stresses of steel tube layer

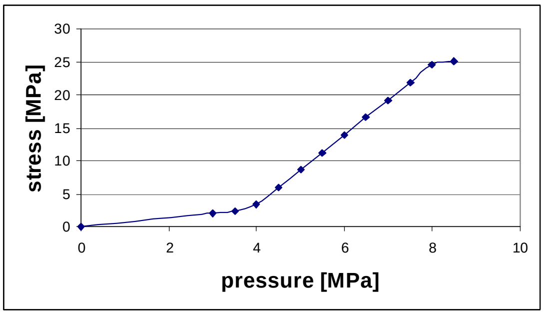

Fig. 7: Equivalent stresses of HDPE layer with respect to internal pressure

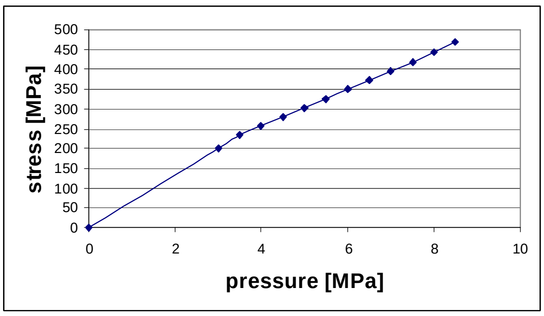

Fig. 8: Equivalent stresses of steel tube layer with respect to internal pressure

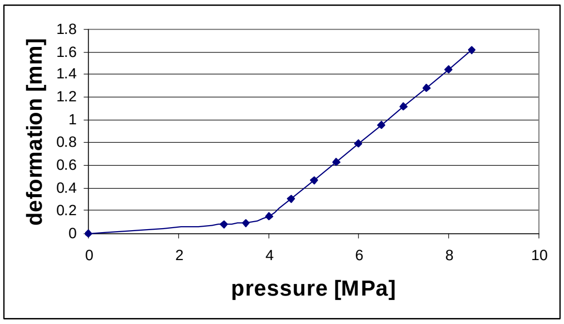

Fig. 9: Deformations with respect to internal pressure

3 Composite metal reinforced pipe (CMP) subject to external load

The same model is used to simulate the mechanical behavior of the CMP pipe under external load. The model is meshed again using the same parameters in ANSYS®. The only difference is that in the current analysis the option “Large Deflection” was active, which means that the solver took under consideration the progressive change of pipe’s geometry. The boundary conditions are shown in Figure 10. The computed displacements are presented in Figure 11. The undeformed position of the pipe is shown in the same figure as a wireframe. The equivalent stresses of the HDPE and steel tube layer are shown in Figures 12 and 13 respectively. The developed stresses aren’t uniform and the areas with the maximum stresses are indicated. Further, the mechanical behaviour of the CMP pipe has been studied for a range of external loads ranging from $F=200$ to 1100 N. The computed stresses of the HDPE layer are shown in Figure 14, of the steel tube layer in Figure 15 and the displacements in Figure 16. As it can be seen from the figures the nonlinear behaviour of the CMP pipe is found for F=800 N, although steel goes into the plastic region for F=600 N. The HDPE layer remains in the elastic region.

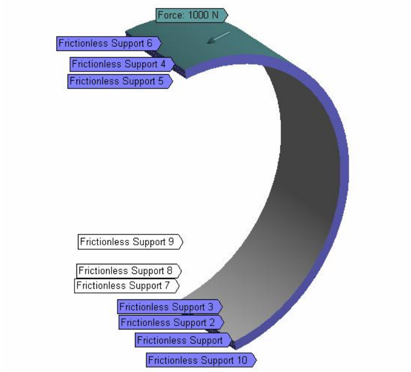

Fig. 10: Boundary conditions

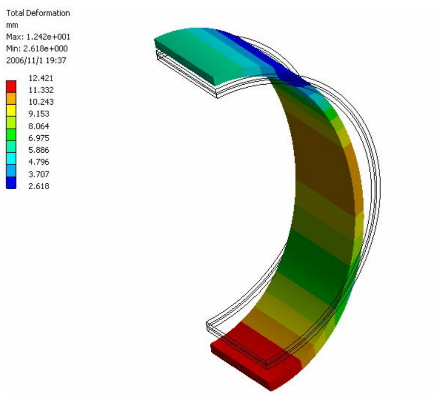

Fig. 11: Total displacements

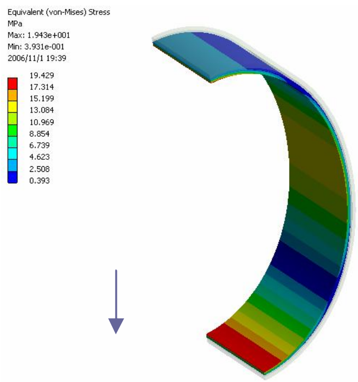

Fig. 12: Equivalent stresses of HDPE layer

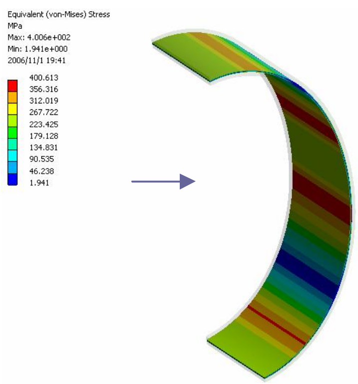

Fig. 13: Equivalent stresses of steel tube layer

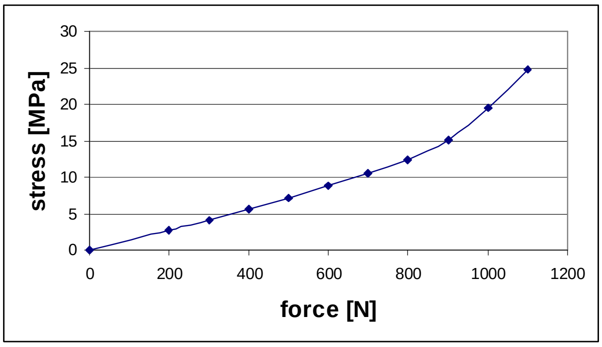

Fig. 13: Equivalent stresses of HDPE layer versus external load

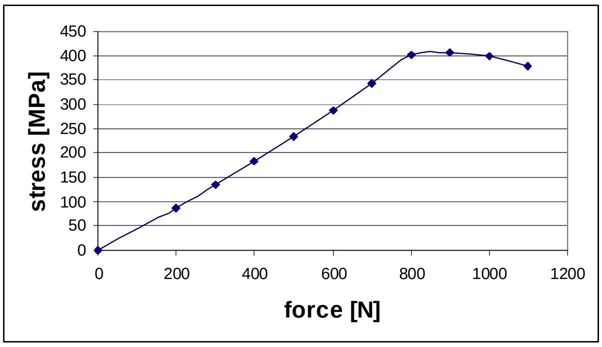

Fig. 14: Equivalent stresses of steel tube layer versus external load

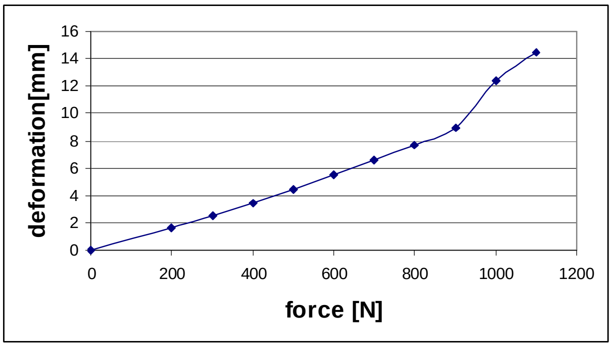

Fig. 15: Deformations versus external load

4 Composite metal reinforced pipe (CMP) subject to internal pressure and external load

The combined case where the CMP pipe is subject to internal pressure and external loads is considered. The different stress state of the CMP pipe developed for the two cases and the non linear character of the mechanical behavior led us to the conduction of a parametric analysis. Two cases where considered. In the first case the internal pressure is high, between p=4.5 to 6.5 MPa. In the second case internal pressure is medium between p=0 and 2.5 MPa. In both cases the external load is between F=500 to 700

N. The method Design Of Experiment (DOE) was implemented to specify the design points that are used to construct the response surfaces. For the first case the design points are shown in Table 2.

	Pressure [MPa]	Load [N]
1	5.5	600
2	4.5	600
3	6.5	600
4	5.5	500
5	5.5	700
6	4.5	500
7	6.5	500
8	4.5	700
9	6.5	700

Table 2: Design points using DOE for the first case

The response surfaces regarding the equivalent stresses of the HDPE layer are shown in Figure 16, of the steel tube layer in Figure 17 and the deformations in Figure 18. As it can be seen from the figures the internal pressure is dominant regarding the mechanical behavior of the CMP pipe.

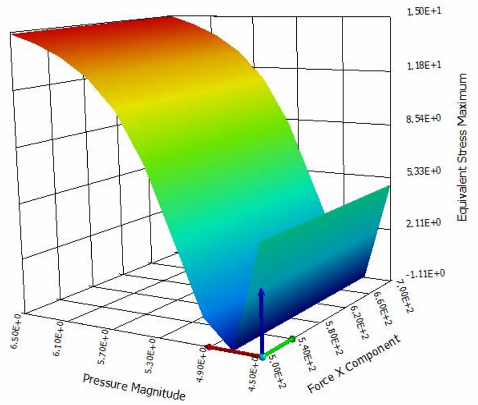

Fig. 16: Equivalent stresses of HDPE layer versus internal pressure and external load

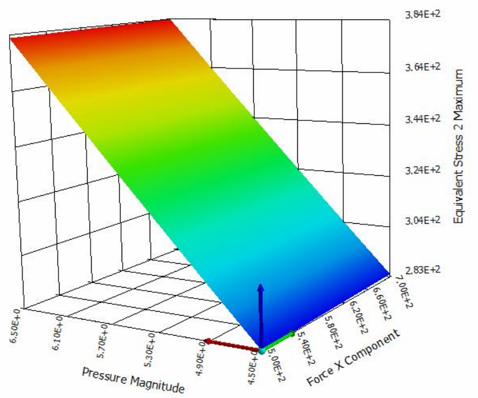

Fig. 17: Equivalent stresses of steel tube layer versus internal pressure and external load

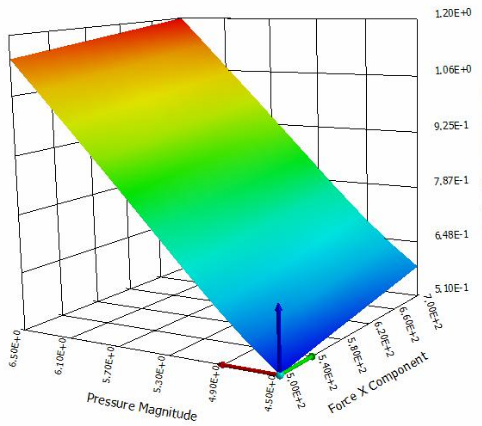

Fig. 18: Deformations versus internal pressure and external load

For the second case the design points are shown in Table 3.

	Pressure [MPa]	Load [N]
1	1.25	600
2	0	600
3	2.5	600
4	1.25	700
5	1.25	500
6	2.5	700
7	0	700
8	0	500
9	2.5	500

Table 3: Design points using DOE for the second case

The response surfaces regarding the equivalent stresses of the HDPE layer are shown in Figure 19, of the steel tube layer in Figure 20 and the deformations in Figure 21. As it can be seen from the figures the external load is dominant regarding the mechanical behavior of the CMP pipe.

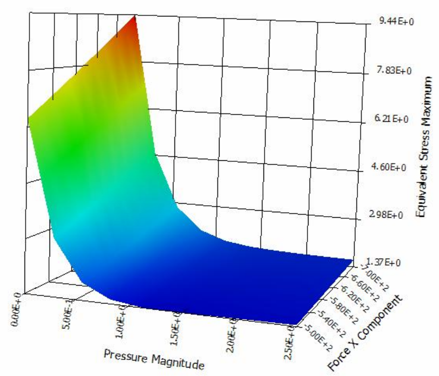

Fig. 19: Equivalent stresses of HDPE layer versus internal pressure and external load

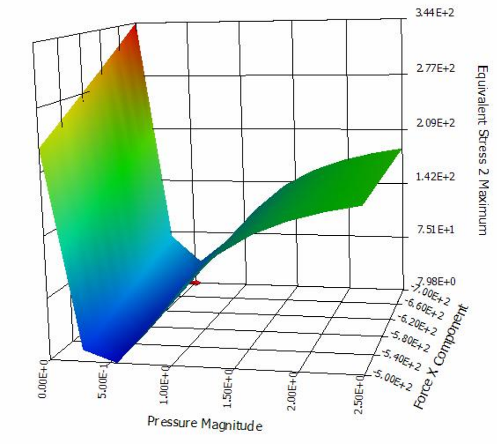

Fig. 20: Equivalent stresses of steel tube layer versus internal pressure and external load

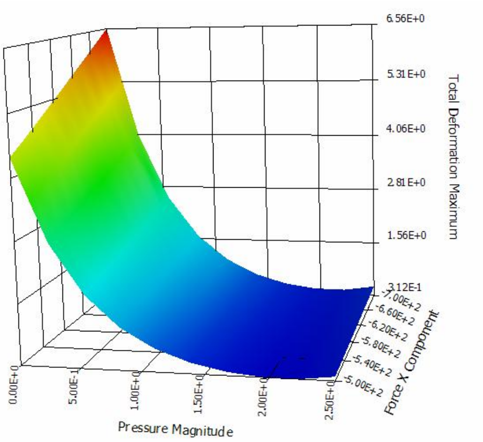

Fig. 21: Deformations versus internal pressure and external load

5 Conclusions

In the present work, the mechanical behaviour of metal reinforced composite pipes subject to internal pressure and external loading is considered. Numerical nonlinear models are developed to analyze the stress-strain state (SSS) in such pipes during loading. The paper focuses on the nonlinear response of composite pipes consisting of two HDPE layers and a steel tube layer. A parametric analysis regarding the internal pressure and external loading has been conducted separately and using the DOE method.

The analyses show that the internal pressure is dominant regarding the mechanical behaviour of the pipe for high pressures; while for low pressures external loads are more significant. The maximum stresses are not developed at the same areas for the two load cases and the mechanical behaviour of the pipe is highly nonlinear. For this reason it is considered very important for the designers to be able to predict the response of the CMP pipes using experimental results and the power of nonlinear numerical models.

In addition, we rely for these analyses totally on existing CAE software: the steel tube cylinder and the polyethylene cover are modelled as different solid parts that are assembled using Autodesk Inventor®. The solid model is –then- introduced for processing with ANSYS®.

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